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An approximation algorithm for vehicle routing problems with hierarchized traffic network

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Abstract

Efficient delivery planning for freight transport is required for reducing environmental load and logistical costs. By using an actual traffic condition, a more realistic delivery plan, increased delivery work efficiency, and CO2 reduction will be possible. An algorithm for quickly obtaining a best solution is required to solve actual vehicle routing problems of large-scale networks and fluctuating delivery costs. The purpose of our research was to solve vehicle routing problems on a large-scale road network that can be applied to actual vehicle routing problems. Our proposed algorithm uses a hierarchical traffic network model composed of two layers according to the frequency of road use. The algorithm is based on tabu search, and the hierarchical traffic network is applied to a generation strategy of the neighborhood solution. Specifically, priority of movement of neighborhood solutions for generating a neighborhood solution is given to delivery points connected in frequently used roads. By using travelling salesman and simple vehicle-routing benchmark problems as a first step in our computing, we confirmed that the proposed algorithm can quickly provide a better solution than the non-application of the proposed algorithm. Furthermore, the effectiveness of the proposed algorithm is discussed by using a virtual vehicle routing problem based on an actual road network.

Keywords: Logistics; vehicle routing problems; tabu search; traffic network

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1. Introduction

Against the background of the need to reduce CO2 emissions and the expanding logistics market, there is an increasing demand for more efficient urban freight transport. Transportation planning that tackles large-scale logistics problems and can be applied to actual vehicle problems is required. The vehicle routing problem (VRP), in which the goal is to calculate a route to a customer that minimizes total delivery cost in consideration of various restrictions, such as the location of depot, the number of vehicles, vehicle load capacity, and delivery time windows, is one of these logistics problems. Finding a solution to this problem becomes very difficult as the number of customers increases because the VRP is a type of NP-problem. Therefore, a practical algorithm for solving the VRP is required, and metaheuristic approaches are expected to be used as optimization techniques for large VRPs. Many metaheuristic approaches have been proposed, including several based on the tabu search algorithm. A strategic method in which the features of a road network are taken into account would be effective for treating large-scale networks. A characteristic of tabu search is that it uses information about how to search for a solution. Each vehicle route search in the VRP corresponds to the travelling salesman problem (TSP). Therefore, methods for applying the TSP to a VRP and generating an approximate solution have been proposed. Willard (1989) was the first to apply tabu search that used 2-OPT and 3-OPT for solving the TSP. Pureza and França (1991) used tabu search to generate approximation solutions by swapping the vertices between two routes. A method similar to 2-OPT for applying the exchange of partial routes between vehicles has been proposed (Gendreau *et al.*, 1994). A method for generating an initial solution consist of a random algorithm and a greedy algorithm. The Greedy Randomized Adaptive Search Procedure (GRASP), a method that combines the random and greedy algorithms, was proposed to generate an initial solution (Feo *et al.*, 1994), and it was confirmed that a good solution can be obtained by using tabu search with this initial solution.

An ideal situation is assumed with most current methods. Many do not take into account an actual road situation. With respect to actual roads, Yokota *et al.* (2011) showed that truck routes can be constructed in a two-layer traffic network model based on frequency of use by analyzing truck probe data which is used as a transport. Therefore, we thought that obtaining an optimal solution by applying the frequency of use of such routes to the move strategy for solution generation of tabu search and by giving priority to the routes between customers located on frequently used roads.

We propose an approximate solution algorithm for the VRP by taking into account of the two-layer traffic network model. We treat the VRP of delivering a load at minimum transit cost using a vehicle of uniform capacity that leaves a single depot (CVRP). First, we describe the proposed algorithm and the results of applying it to the move strategy of the TSP. Next, we discuss the application of the TSP with the proposed algorithm to the VRP and the results of applying the proposed algorithm to the exchange of partial routes.

2. Features of hierarchical traffic network model

Yokota *et al*. (2011) used truck probe data to devise a traffic network model composed of two layers according to the use frequency of links between roads. One layer is called the high-frequency-network (HFN) and the other the low-frequency-network (LFN). The HFN is the upper-layer network, which consists of roads frequently or commonly used by freight vehicles, such as highways and major roads. The LFN is the lower-layer network, which consists of roads rarely used by freight vehicles, such as ordinary and local roads. Many trucks gain access to the HFN from the LFN. They then drive along a highway for a while and exit near their destination. There are different features between the two networks. Table 1 lists the features of each layer. The ratio of size (the length of the network) of high-and low-frequency networks is about 26% to 74%, and the travel time ratio is 87% to 13%. The average speed is 25.03 km/h on the HFN and 16.87 km/h on the LFN. The data show that vehicles spend roughly 90% of the time on the HFN, drivers use the HFN for long-distance travel. This is because the traffic conditions on the HFN are smoother. Moreover, the road conditions (such as road facilities, number of lanes, and road width), reliability, and safety of the HFN are better.

Table 1. Features of hierarchical traffic network model

	Data size ratio [%]	Time spent ratio [%]	Average speed [km/h]
high-frequency-network (HFN)	26	87	25.03
Low-frequency-network (LFN)	74	13	16.87

3. Vehicle routing problem

3.1. Prerequisites for VRP

In this paper, we consider the VRP, in which a commodity of quantity d_i is to be delivered to each customer $i \in N$ from a single depot $\{0\}$ by independent delivery vehicles of identical capacity c. The prerequisites of the VRP are as follows:

- After the vehicles leave the depot and visit customers, they return to the depot.
- The number and maximum capacity of the vehicles are given.
- The customer's positional coordinates and capacity are given.
- The quantity of the deliveries to each customer is filled in one visit.
- The cost of each delivery is calculated with the Euclidean distance between customers.
- The loading quantity of each delivery route is constrained by the capacity of the vehicle and is assumed to be below the capacity of the vehicle.

3.2. Formulation

The typical formulation for the single-depot VRP is as follows.

Minimize

$$z = \sum_{k \in K} \sum_{(i,j) \in V} c_{ij} x_{ijk} \tag{1}$$

Subject to

$$\sum_{k \in K} \sum_{j \in V} x_{ijk} = 1 \qquad \forall i \in N \tag{2}$$

$$\sum_{i \in N} d_i \sum_{j \in V} x_{ijk} \le q \qquad \forall k \in K \tag{3}$$

$$\sum_{j \in V} x_{0jk} = 1 \qquad \forall k \in K \tag{4}$$

$$\sum_{j \in V} x_{i0k} = 1 \qquad \forall k \in K \tag{5}$$

$$\sum_{i \in V} x_{ihk} - \sum_{j \in V} x_{hjk} = 0 \qquad \forall h \in N, \forall k \in K \tag{6}$$

$$\sum_{j \in V} \sum_{j \in V \setminus S} x_{ij} \geq 1 \qquad \forall S \in V, (S \neq \phi, S \neq V) \tag{7}$$

$$x_{ijk} \in \{0,1\} \qquad \forall i, j \in N, k \in K \tag{8}$$

where,

- z : total travel cost
- K : vehicles
- k : set of the number of vehicles
- $i.j.h$: set of the number of customers
- c_{ij}: travel cost from customer i to customer j
- x_{ijk}: = 1 if travelled from customer i to customer j
  = 0 otherwise
- N : set of the number of customers = {1, 2, 3,・・・, n }
- V : set of the number of customers and depots
- S : not empty subset of N (not equal to N)
- d_i : customer i loading quantity (non-negative)
- q : vehicle capacity

The objective function z of the total cost minimization is expressed by Eq. (1). Constraint (2) shows that each customer is served by exactly one vehicle. Constraint (3) expresses vehicle capacity constraints. Constraints (4) and (5) show that all vehicles start from a depot and the vehicles return to the same depot. Equation (6) expresses that a vehicle does not visit at customer who it has already visited. The sub tour S elimination constraints are given in Constraint (7). Constraint (8) shows that the variables x_{ijk} are binary, indicating that they depend on travel from customer i to customer j.

4. Our approach based on tabu search

Our proposed algorithm is based on the tabu search algorithm. We believe that a hierarchical traffic network is applicable to the solution generation strategy. In this chapter, we describe the general tabu search algorithm and our proposed algorithm in which the hierarchical traffic network is applied to the generation strategy of the neighborhood solution.

4.1. Tabu search algorithm

Tabu search is a heuristic algorithm for combinational optimization problems based on a local search. The metaheuristic approach using tabu search to obtain the global optimization solution, which is not local optimization, was proposed by Glover (1977, 1989) and Glover *et al.* (2002). Tabu search explores a neighborhood for a current solution and is updated with the best solution. The local search finally selects the local optimum solution that is the best solution in the neighborhood. Unlike local search, tabu search keeps searching for the best solution in a neighborhood even if the generated solution is worse than the current one. The recently examined solutions are forbidden by using the tabu list to avoid cycling. A forbidden move is inserted at the end of the tabu list and the first element from the list is removed. Thus, movement continues by returning the element from the tabu list. The tabu search procedure is as follows:

Step 1. Generate an initial solution.

Step 2. Search for neighborhood solutions obtained by using movement not included in the tabu list.

Step 3. Store the movement to the tabu list.

Step 4. Repeat search for the best solution by giving permission for movement even if the best local solution has been obtained.

Step 5. Finish the search when the termination condition which was set previously, is satisfied.

4.2. Construction of initial solution

The procedure for creating an initial solution includes a method of generating a random and low evaluating solution. The methods available include the saving (Clarke-Wright, 1964), optimal-partitioning (Beasley, 1983), and region-portioning (Gillet-Miller, 1974) (Haimovitch *et al.*, 1985) methods.

An initial solution is generated by using a region-portioning method with clustering analysis. The provided graphs are partitioned into the number of vehicles by using Ward's method (Ward, 1963), which minimizes the sum of distances within two (hypothetical) clusters. The loading quantity is not considered when calculating the initial solution with Ward's method. Therefore, in the initial solution, each loading quantity of vehicles is allowed to exceed the capacity of the vehicle. The initial route in each area is generated by connecting the nearest vertex.

4.3. Generation of neighborhood solutions

The generation of a neighborhood solution is one of the most important factors in tabu search. This requires an efficient method for generating an approximate solution that enhances the potential for improved solutions to be included in a neighborhood. Many methods for generating neighborhood solutions have been examined. Typical ones are the λ-OPT ($\lambda > 2$) exchange that exchanges some of the solutions, two-vertex exchange movement, and one-vertex insertion movement.

In our algorithm, we apply the idea of a hierarchical traffic network model to the strategy for generating neighborhood solutions. Fig. 1 shows the procedure of our algorithm based on tabu search. In Fig. 1, the upper layer is an HFN and the lower layer is an LFN. Our algorithm uses the composition of the hierarchical traffic network model to a candidate list strategy. As previously explained the hierarchical traffic network model that Yokota *et al.* proposed is classified into two layers based on the frequency of road use. The upper layer is composed of roads used with high frequency and for long-distance driving and the lower layer is composed of roads used with low frequency and for driving around the origin or destination. We believe that the solution might change significantly if it generates a change in the HFN edges because such an edge is a frequently used long-distance trip. We give priority of movement to points connected within the HFN. As a result, these points are optimized. The points connected within the LFN are moved only if the effect of change in the solutions is not gained in the HFN. We adopted a move strategy in which neighborhood solutions are generated by giving high priority to edges (i, j) for frequently used long-distance-routes. Fig. 2 shows our algorithm for generating neighborhood solutions for vehicle routing.

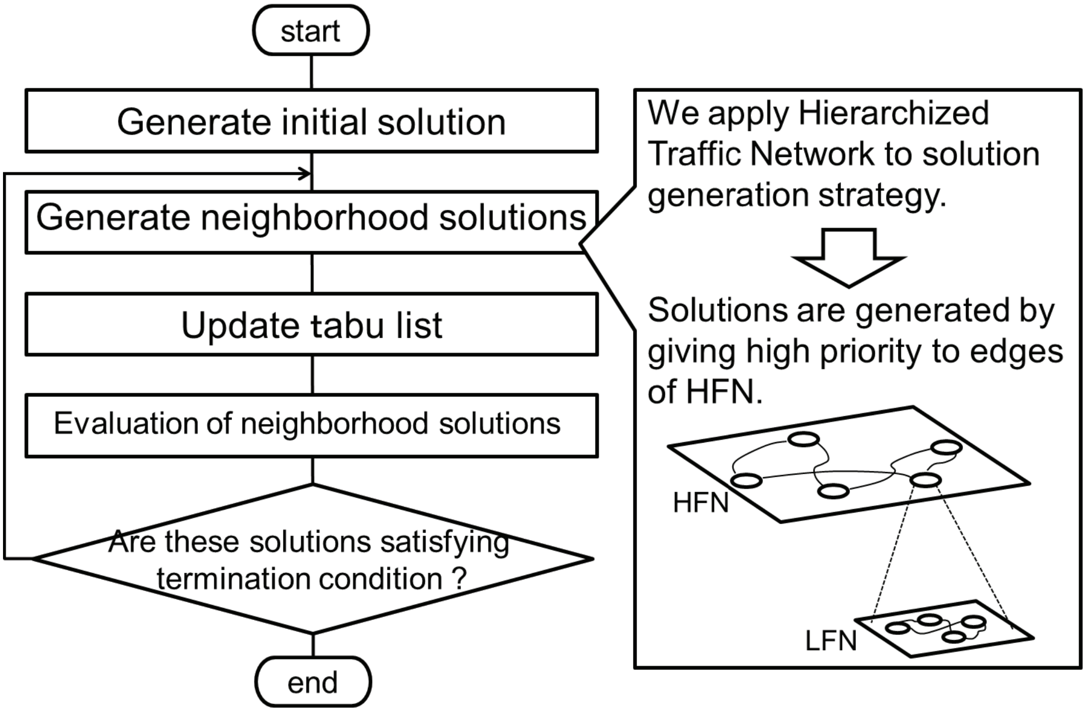
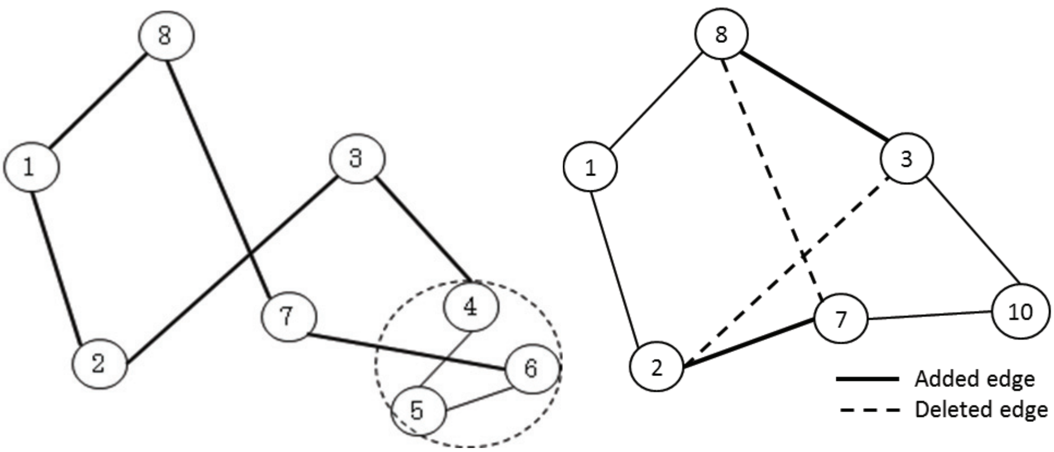


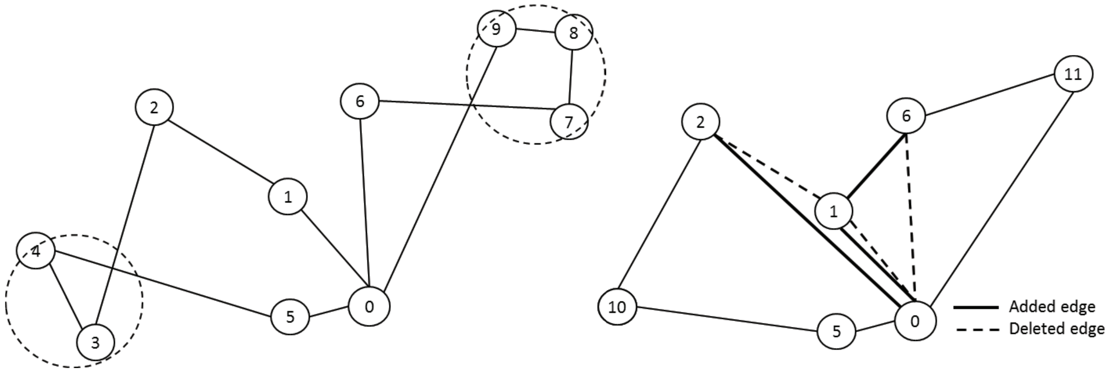
Fig. 1. Procedure of proposed algorithm based on tabu search



(a) Current solution (b) Neighborhood solution

Fig. 2. Generation of neighborhood solution using priority moves

In Fig. 2, edges (4, 5) and (5, 6) are in the LFN, and the other edges are in the HFN. Vertices 4, 5, and 6 connected in the LFN are selected as hypothetical vertex 10. Vertices 1, 2, 3, 10, 7, and 8 of the HFN are exchanged in an early process. In this example, edges (7, 8) and (2, 3) are selected as the move points, and they are moved by using the 2-OPT method. As a result, edges (2, 7) and (3, 8) are newly generated. The move in the HFN is executed repeatedly. In the next process, the best solution is explored by using the obtained solution as a new initial solution, and vertices 4, 5, and 6 are moved repeatedly in the LFN. In the VRP, to which this proposed algorithm is applied, the vertices of the HFN of each graph are moved based on priority. Fig. 3 shows the re-composition of a fractional graph with a priority move.



(a) Current graph (b) Re-composition graph

Fig. 3. Re-composition of fractional graph with priority move

In each route where the start point is depot 0, edges (3, 4), (7, 8), and (8, 9) are in the LFN. Vertices 3 and 4 are set as hypothetical vertex 10, and vertices 7, 8, and 9 are set as hypothetical vertex 11. Vertices 1, 2, 5, 6, 10, and 11 of the HFN are moved in an early process.

5. Computational results

We applied the proposed algorithm to the TSP and VRP benchmarks first, because these problems' optimal solutions are clear. We believe that the proposed algorithm is effective if an approximate solution is quickly obtained using it.

5.1. Application to TSP

The instance of the multiple travelling salesman problem (MTSP) is obtained by setting q= ∞ of Constraint (3). The MTSP instance is transformed into the TSP instance by integrating a fractional graph. That is, the TSP instance is a problem that simplifies the constraint of the VRP. We believe that the proposed algorithm might be effective in the VRP if we can quickly obtain a good solution when using it for the TSP. We used problems from the benchmark library for the TSP (TSPLIB), which is available at http://www2.iwr.uni-heidelberg.de/groups/comopt/software/TSPLIB95/. The two benchmark problems (att48, att532) used in this paper are treated as problems of locations on a map. The effectiveness of the proposal algorithm is confirmed by obtaining the simulation results from applying the proposal algorithm to such benchmark problems. There is no HFN or LFN information in the benchmarks; therefore, we assumed an HFN and LFN based on distance. In the benchmarks, long edges are treated as high-frequency roads and short edges are treated as low-frequency ones. This is because the former are used for long-distance trips and the latter are used for short-distance trips. The long edges are given priority of movement, and moves with the vertices are executed. In this way, the search for an approximate solution using long-distance edges is executed. After a prescribed number of repeats of the search are executed, approximate solution generations with the short edges are executed. The criteria of the edge classification based on distance are assumed as a parameter. In this simulation, the parameter is termed "classification rule". A virtual hierarchical traffic network with long edges of the upper layer and short edges of the lower layer is constructed using this parameter.

5.1.1. Results of benchmark att48

Fig. 4, Fig. 5 and Table 2 show the results for att48. Fig. 4 shows the trend in route costs with non-classification and classification rules 100 and 300. “Classification rule 100” is the result calculated by preferentially moving vertices where the distance is over 100, “classification rule 300” is the result calculated by preferentially moving vertices where the distance is over 300, and "non-classification" means that the network is not hierarchical.

The cost variation width with the classification rule (using a layer) is bigger than with non-classification in the initial process. This is because the solutions changed greatly by the move that concentrated the long-distance vertices as shown in Fig 4. Table 2 lists the best solutions (the minimal route cost), error rates, and the iteration counts when the best solution is obtained. The error rate ε is calculated with the best solution z_{best} and optimal solution z_{opt} as

$$\varepsilon[\%] = \frac{z_{best} - z_{opt}}{z_{opt}} \times 100 \tag{9}$$

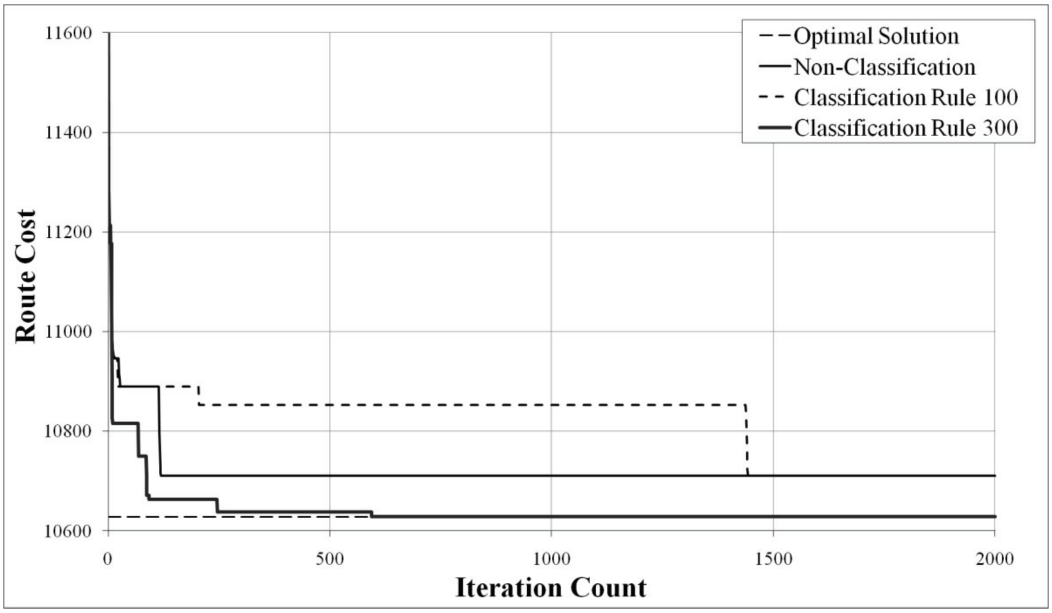
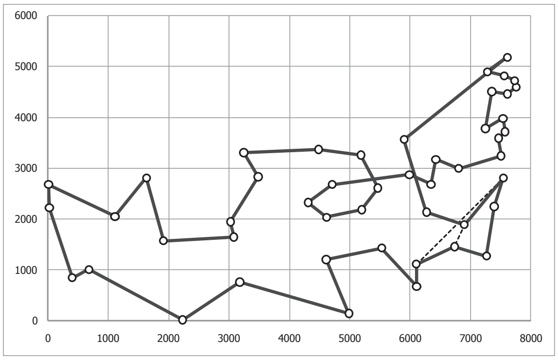
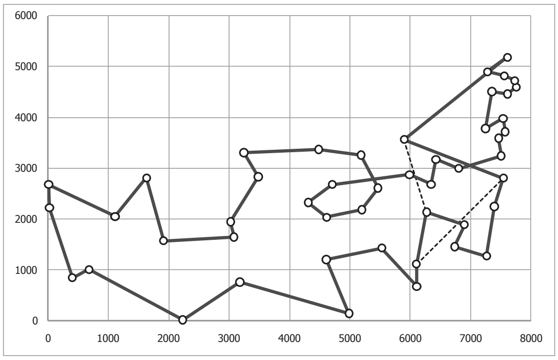


Fig. 4. Trend in calculation results (att48)



(a) Move with non-classification



(b) Move with classification

Fig. 5. Generation of neighborhood solutions in initial process

In this test, the tabu list size is N, and the iteration limit with the classification rule is 500. After the search with the classification rule is repeated 500 times, the search with the non-classification rule is repeated. The iteration count and the solution accuracy improved most when the classification rule was 300. The best solution then is an optimum solution. The reason the optimum solution was obtained in this case was that the route cost changed greatly at the early stage. On the other hand, the tendency for the solution accuracy to worsen by a set value of the distance became apparent.

Table 2. Calculation results for att48

Classification Rule	Iteration count	Best solution	Error rate ε [%]
Non-classification	120	10711	0.78
100	1444	10711	0.78
200	433	10712	0.79
300	595	10628	0.00
400	731	10845	2.04
500	534	10711	0.78

Optimal solution = 10628

5.1.2. Results of benchmark att532

Fig. 6 and Table 3 show the calculation results for att532. The optimal solution was not obtained, but the best solution within this test was obtained the fastest at the time of classification rule 150. Some solutions with classification become worse compared with non-classification in this case; therefore, it is important to consider the value of the classification rule.

These two results of the TSP benchmark show the possibility of quickly obtaining the best solution by using the hierarchical traffic network. However, there are some cases where the solution accuracy with the hierarchical traffic network is worse than the result of the non-hierarchical network. This reason is the classification rule that classifies the benchmark networks into the HFN and LFN. If the classification rule is not appropriate to the problem, our proposed algorithm is deemed as not effective. This means that the constitution of a hierarchical traffic network has a decisive effect on the solution accuracy of our proposed algorithm. In the benchmark problem, we calculated with some classification rules and confirmed the effectiveness of our proposed algorithm when using an appropriate classification rule. This issue is the same as in actual problems. That is, in actual problems, it is necessary to construct a hierarchical traffic network in which the proposed algorithm will be effective. Therefore, the evaluation of the proposed algorithm using a hierarchical traffic network using rules based on an actual road network is necessary.

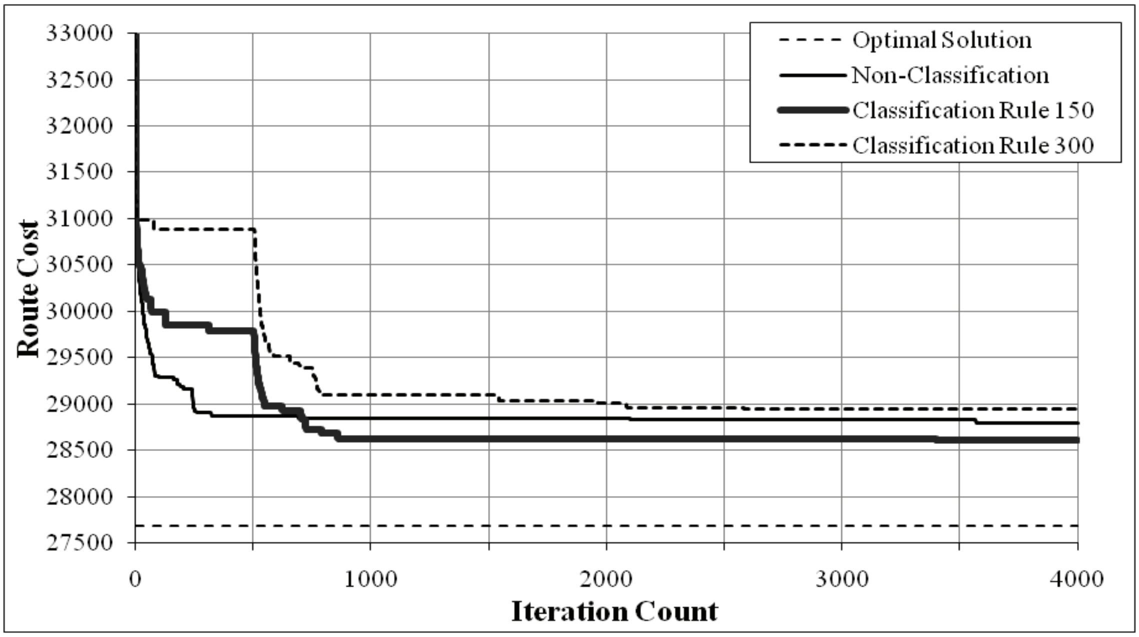


Fig. 6. Trend in calculation results (att532)

Table 3. Calculation results for att532

Classification Rule	Iteration count	Best solution	Error rate ε [%]
Non-classification	3572	28795	4.01
50	2475	28766	3.90
100	3998	28617	3.36
150	3401	28617	3.36
200	1724	28826	4.12
250	4173	28656	3.50
300	4157	28922	4.46
350	4868	28815	4.09

Optimal solution = 27686

5.2. Application to VRP

5.2.1. Results of benchmark A-n32-k5

Our test used medium-sized CVRP instances proposed by Augerat (1995). The instances are available from the TSBLIB. Two or more benchmark instances were stored in the TSBLIB, and the results of applying the proposed algorithm to the simplest problem, A-n32-k5, are described.

The A-n32-k5 problem was given a set of N (=32) nodes, single depot, five trucks, the capacity (=100) of the multiple vehicles, and demand at each node. In the first-stage, the clustering analysis using Ward's method was executed, and a graph of the problem was decomposed into groups of the multiple vehicles. Next, the vertices of a neighborhood were connected with each group and an initial solution was generated [Fig. 8(a)]. Each route generated an approximate solution by using the proposed algorithm, and the algorithm in Fig. 1 was used for the movement of vertices between the groups. These movements were executed on the set classification rule. The size of the tabu list used for this process was "N + the number of vehicles – 1", and the set parameter of the iteration count of the classification rule (the timing of the switch to the low-layer network search) was 100. Furthermore, after the search with the classification rule was repeated 100 times, the search with the non-classification rule was repeated.

Fig. 7 shows the trend of the solution calculated with and without the proposed algorithm. In the initial search, the change in the solution with the clustering rule applied was large. This is the same trend as that seen for the TSP. Table 4 lists the results when the solutions were calculated with and without the proposed algorithm.

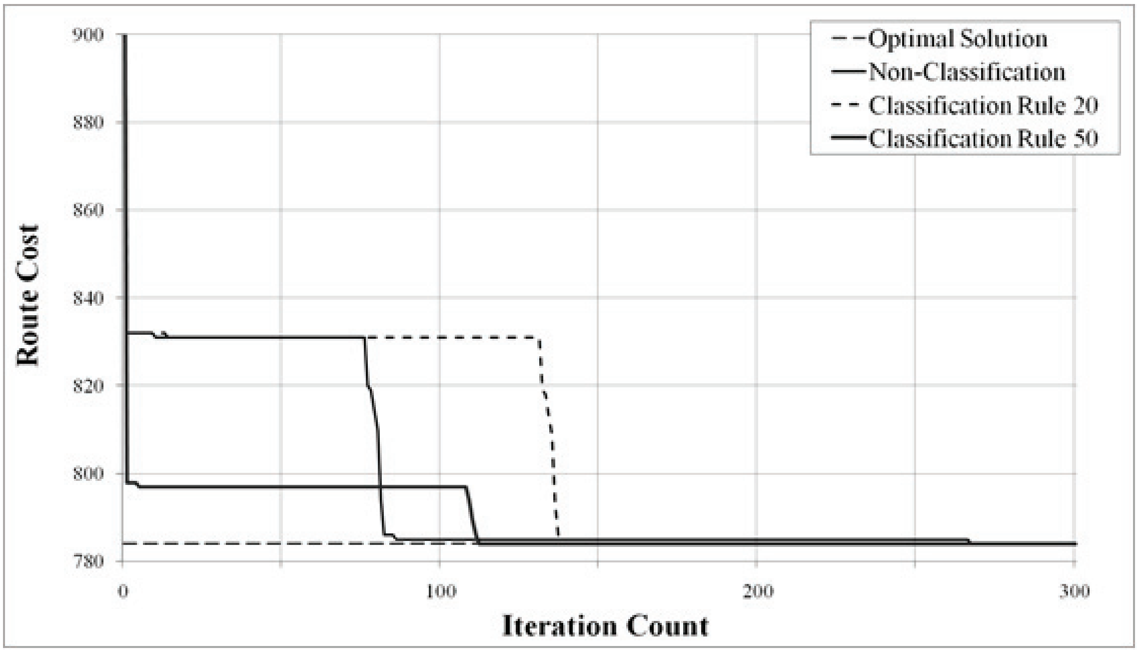


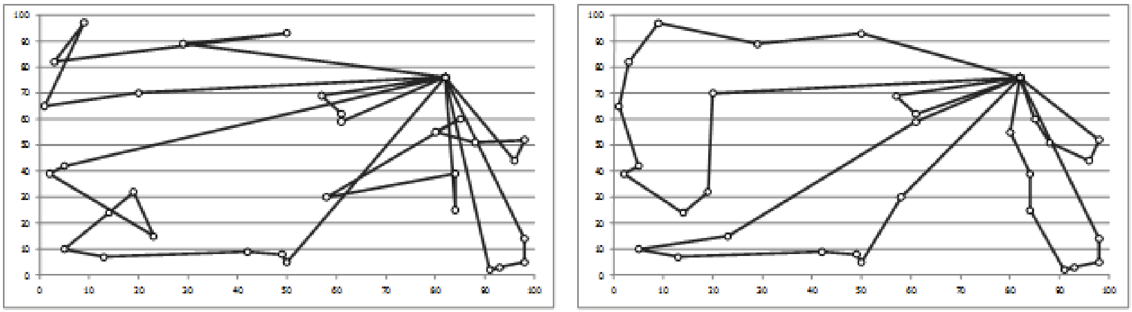
Fig. 7. Trend of solution calculated with and without proposed algorithm (A-n32-k5).

Table 4. Calculation results for A-n32-k5

Classification rule	Iteration count	Best solution	Error rate ε [%]
Non-classification	268	784	0.00
10	268	784	0.00
20	139	784	0.00
30	488	784	0.00
40	506	784	0.00
50	113	784	0.00
60	122	784	0.00

Optimal solution = 784

The best solution was obtained at the early stage in each case because the initial solution obtained using the clustering analysis provided a composition close to that for an optimum solution [Fig. 8(b)]. In this problem, the optimum solution was obtained with all classification rules. In particular, the optimum solution with the smallest iteration count was obtained with classification rule 50. The non-classification rule fell into a local solution at the early stage and required iterative calculation to obtain the optimum solution. In other classification rules, the iteration count of classification to the optimum solution was larger than that of non-classification. This shows that the network composition of the VRP affects solution accuracy.



(a) Initial solution (b) Optimal solution

Fig. 8. Examples of solutions (A-n32-k5).

5.2.2. Results of virtual problem using actual road network

We calculated the CVRP using an actual road network to confirm the effectiveness of our proposed algorithm in actual problems. We used digital road map (DRM) data that the Japan Digital Road Map Associate provides as an actual road network. Thirty-one virtual delivery points and a virtual single depot (N=32) were set on the map. Fig. 9 shows the locations of the delivery points and the depot on the map. The coordinates of these points are shown in Appendix A. The route information between all the points was calculated by minimum time routing. In table A1, travel time of each road link, calculated based on the speed limit and road link length, in the routing was used as the routing cost. If traffic information was available, the actual travel time provided as real-time traffic information was used for the routing. The origin-destination (OD) cost matrix between all delivery points created by routing is shown in Appendix

B. Based on Eq. (1), the optimal solution in which total delivery time becomes the minimum cost is calculated with the OD cost matrix.

Constraint conditions in this problem, such as the number of vehicles, delivery load capacity, and each customer's demand set value, were the same as benchmark problem A-n32-k5. All vehicles departed from a depot, distributed goods ordered by each customer, and came back to the depot.

Furthermore, the hierarchical traffic network in this problem consisted of an LFN of short travel-time ODs and an HFN of long travel-time ODs. The long travel-time ODs were given priority of movement and the best solution and generation time for this problem were calculated. The best solution and generation time were compared using a non-hierarchical network, and the effectiveness of the proposed algorithm was evaluated. The threshold of the travel time to constitute a hierarchical traffic network (classification rule) was assumed as a parameter. Fig. 10 and Table 5 show the trend of calculation results of the actual network problem. The “route cost” in Fig. 10 is in seconds. As a result of having calculated the solution using classification rules, when the classification rule was 300 seconds, the best solution was calculated at the earliest stage. Fig. 10 shows the trend of the representative classification rule. The initial solution to this problem was calculated similar to the benchmark problem, and Ward’s method using the position coordinates of the delivery points was used. Fig. 11 shows the initial and best solutions in this calculation.

Using the problem based on an actual network, we confirmed that the proposed algorithm can quickly provide a better solution than with the non-application method. In the future, we will clarify the constitution of a hierarchical traffic network using road attributes such as expressways or local streets after having evaluated their compatibility with the proposed algorithm.

Fig. 9. Delivery points and depot

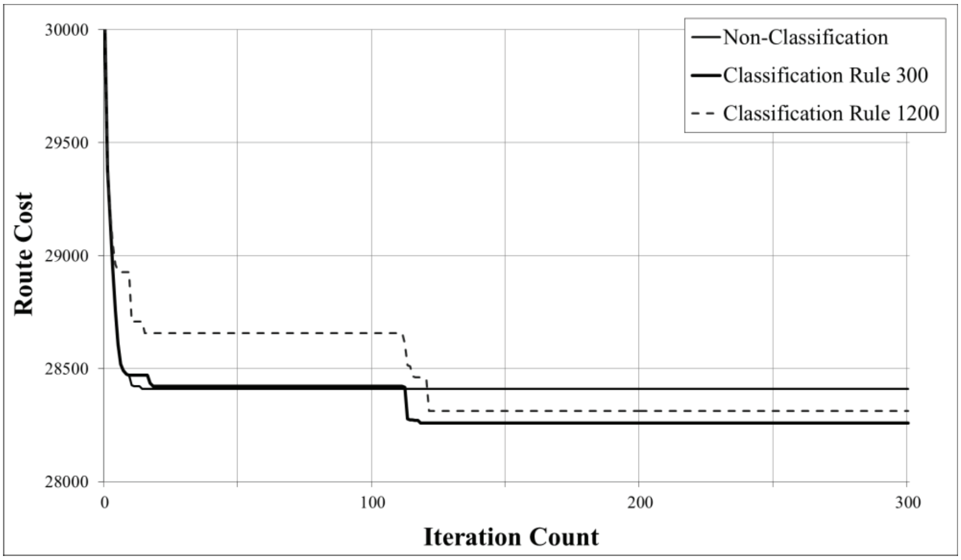
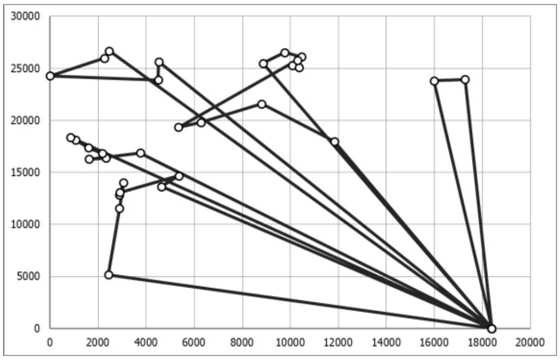


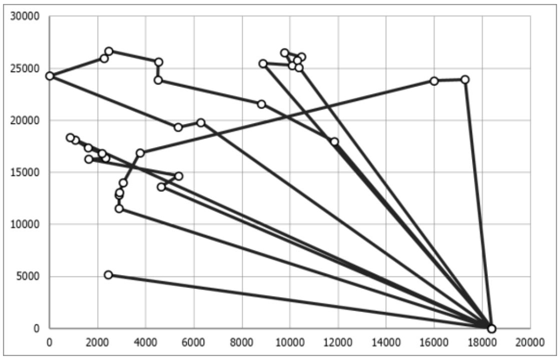
Fig. 10. Trend of calculation results (using actual network)

Table 5. Calculation results (using actual network)

Classification rule	Iteration count	Best solution
Non-classification	15	28411
150	19	28411
300	119	28260
600	155	28411
900	16	28658
1200	122	28313
1500	16	28658



a) Initial solution



(b) Best solution (classification rule = 300)

Fig. 11. Examples of solution (using actual network)

6. Conclusion

We focused on a hierarchical traffic network model constructed of two layers on the basis of road-use frequency, and examined our proposed algorithm of applying use frequency to the move strategy of the solution of the tabu search. Our algorithm gives priority of movement to a customer connected within a high-frequency traffic network. We confirmed the effectiveness of the proposed algorithm by first using the TSP and a simple VRP benchmark problem. In the benchmark evaluation, a hierarchical traffic network was constructed based on the distance of the vertex interval (edge length) because the original benchmark network does not support the use frequency of traffic. By using the benchmark problems, we confirmed that the proposed algorithm can quickly provide a better solution than with the non-application method. Next, we discussed its effectiveness by using a virtual VRP based on an actual road network.

From these evaluations, we confirmed that effectiveness of the proposed algorithm depends on the construction of a hierarchical traffic network. Therefore, a more practical evaluation is necessary by using an actual traffic network which was layered based on the feature of a hierarchical traffic network shown in Table 1. We will apply the proposed algorithm to actual vehicle routing problems using a hierarchical traffic network in which the feature is more reflected and carry out a practical evaluation.

Acknowledgments

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Appendix A. Delivery points

Table A1 lists the coordinates of delivery points for the actual network problem discussed in this paper. These points were set by referring to the location of an actual convenience store. The first location of the list is the depot.

Table A1. Coordinates of delivery points

Point No	longitude	latitude	Point No	longitude	latitude
1	139.5406	35.30976	17	139.3517	35.46811
2	139.3358	35.52846	18	139.3476	35.47179
3	139.3605	35.54365	19	139.346	35.47442
4	139.3845	35.5252	20	139.5289	35.52432
5	139.4332	35.53929	21	139.3691	35.43572
6	139.3937	35.48362	22	139.5109	35.52452
7	139.4434	35.54883	23	139.3959	35.44176
8	139.3625	35.55099	24	139.4468	35.53788
9	139.3839	35.5433	25	139.4498	35.53581
10	139.3611	35.35499	26	139.3667	35.42566
11	139.3668	35.41361	27	139.3683	35.42724
12	139.4661	35.47161	28	139.4482	35.54242
13	139.377	35.46188	29	139.455	35.54724
14	139.3532	35.45636	30	139.4031	35.48524
15	139.3611	35.45717	31	139.3862	35.43224
16	139.3598	35.46038	32	139.4317	35.50616

Appendix B. Origin-destination cost matrix

Table B1 is the OD cost matrix between all delivery points. This matrix is created by minimum cost routing using the travel-time cost of each road link. These costs were calculated using the regulation speed and road link length of DRM.

Table B1. Cost matrix of delivery points

Point No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1		3132	3004	2859	2380	2425	2508	3017	2830	1621	1903	1863	2369	2293	2263	2306
2	3157		475	676	1066	837	1191	498	761	1701	1254	1555	840	896	895	861
3	3027	475		326	727	708	852	88	380	1571	1124	1415	710	895	765	808
4	2882	676	326		478	497	606	361	229	1612	1165	1168	751	936	806	849
5	2404	1064	725	478		730	127	637	450	1962	1505	690	1123	1286	1156	1199
6	2425	837	708	497	726		854	743	711	1281	824	718	430	604	474	517
7	2529	1192	853	606	127	855		765	577	2087	1630	815	1248	1411	1281	1324
8	3040	498	88	361	638	743	763		318	1644	1197	1326	783	968	838	881
9	2854	761	380	229	450	711	577	318		1793	1346	1140	932	1117	987	1029
10	1621	1697	1569	1612	1954	1276	2082	1642	1793		468	1694	934	858	828	871
11	1923	1251	1123	1167	1502	824	1629	1197	1348	467		1249	489	413	383	425
12	1863	1555	1415	1168	689	718	817	1326	1139	1690	1243		851	1014	884	927
13	2442	911	783	827	1020	342	1147	857	1008	1000	553	760		324	194	237
14	2316	895	886	930	1271	594	1399	960	1111	860	413	1012	251		134	177
15	2285	889	761	805	1146	468	1274	835	985	829	382	887	126	139		42
16	2328	861	804	847	1189	511	1317	877	1028	871	425	929	169	182	42	
17	2400	789	876	920	1261	583	1389	950	1100	944	497	1002	241	169	115	72
18	2482	707	840	865	1343	665	1471	913	1045	1025	579	1083	323	251	196	154
19	2513	676	808	833	1312	697	1440	882	1014	1057	610	1115	354	220	228	185
20	2333	1871	1533	1285	807	1266	862	1444	1257	2239	1792	802	1400	1562	1432	1475
21	2179	1082	955	998	1298	620	1425	1028	1179	723	256	1045	332	283	252	295
22	2238	1711	1373	1125	647	1106	775	1284	1097	2079	1632	642	1240	1402	1272	1315
23	2170	1249	1121	1050	1192	552	1320	1195	1232	935	538	910	499	500	470	512
24	2629	1292	953	706	227	955	189	865	677	2187	1730	915	1348	1511	1381	1424
25	2426	1224	886	639	160	738	190	797	610	1971	1514	712	1132	1294	1164	1207
26	2063	1224	1097	1140	1401	723	1529	1170	1321	607	139	1149	470	394	364	407
27	2088	1250	1122	1166	1426	749	1554	1196	1347	632	165	1174	495	420	389	432
28	2506	1266	928	680	202	847	82	839	652	2079	1622	814	1240	1403	1273	1315
29	2523	1287	949	701	223	878	95	860	673	2111	1654	830	1272	1434	1304	1347
30	2441	996	791	581	613	159	740	826	653	1346	889	734	507	669	539	582
31	2057	1223	1095	1061	1241	564	1369	1168	1276	783	461	989	472	423	393	435
32	2484	1381	1031	704	459	549	586	994	676	1777	1324	623	939	1101	971	1014

Point No	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
1	2378	2460	2491	2344	2159	2288	2170	2608	2406	2042	2068	2488	2505	2441	2031	2484
2	789	707	676	1868	1085	1708	1256	1291	1223	1210	1235	1265	1286	997	1227	1381
3	880	838	806	1529	955	1370	1126	952	885	1080	1105	926	948	799	1097	1031
4	921	865	833	1283	996	1124	1050	706	638	1121	1146	680	701	588	1063	704
5	1271	1343	1312	804	1301	645	1195	227	160	1404	1430	202	223	616	1247	462
6	589	671	703	1265	620	1105	552	954	738	723	749	846	878	159	565	548
7	1396	1471	1440	862	1426	770	1320	189	190	1529	1555	82	95	741	1372	587
8	953	911	879	1441	1028	1281	1199	863	796	1153	1178	838	859	834	1170	994
9	1102	1045	1014	1254	1177	1095	1232	677	610	1302	1327	652	673	653	1277	676
10	943	1025	1056	2241	724	2082	937	2182	1966	607	633	2074	2106	1341	780	1776
11	498	579	611	1796	256	1637	538	1729	1514	139	165	1622	1654	889	463	1324
12	999	1081	1112	805	1041	646	910	917	715	1144	1169	816	832	734	986	623
13	309	391	422	1307	396	1148	415	1247	1032	509	534	1140	1172	407	428	842
14	170	250	218	1559	283	1400	500	1499	1284	368	394	1392	1423	658	425	1094
15	115	196	228	1433	252	1274	469	1374	1158	337	363	1266	1298	533	394	968
16	72	154	185	1476	295	1317	512	1417	1201	380	406	1309	1341	576	437	1011
17		81	113	1548	367	1389	584	1489	1273	452	478	1381	1413	648	509	1083
18	81		31	1630	449	1471	666	1571	1355	534	560	1463	1495	730	591	1165
19	113	31		1662	480	1502	697	1540	1386	565	591	1495	1526	761	622	1197
20	1547	1629	1660		1589	160	1517	955	757	1692	1718	779	785	1231	1534	952
21	367	449	481	1592		1433	334	1525	1310	155	181	1418	1450	685	259	1120
22	1387	1469	1500	159	1429		1357	875	672	1532	1558	712	718	1076	1374	797
23	585	666	698	1518	334	1359		1420	1204	437	463	1312	1344	579	158	1014
24	1496	1571	1540	955	1526	870	1420		277	1629	1655	175	251	841	1472	687
25	1279	1361	1393	757	1310	667	1204	277		1413	1439	108	139	625	1255	471
26	479	561	592	1696	155	1536	437	1629	1413		25	1521	1553	788	363	1223
27	504	586	617	1721	181	1562	463	1654	1439	25		1547	1578	813	388	1249
28	1388	1469	1501	779	1418	709	1312	175	108	1521	1547		76	733	1363	579
29	1419	1501	1532	785	1450	718	1344	251	139	1553	1578	76		765	1395	611
30	654	736	767	1233	685	1075	579	840	625	788	813	733	765		630	435
31	508	589	621	1536	257	1377	156	1469	1254	360	386	1362	1393	628		1064
32	1086	1168	1199	954	1120	796	1014	686	471	1223	1249	579	611	435	1065	